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THE UTILITY OF HF PROPAGATION MODELS FOR PREDICTING THE OPERATING FREQUENCY OF A NON-COOPERATIVE TRANSMITTER

by

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19 ABSTRACT (Continue on reverse if necessary and identify by block number) The High Frequency(HF) radio band, commonly taken to be that portion of the electromagnetic spectrum lying between approximately 3 MHz and 30 MHz, remains a popular and often cost-effective alternative to communications satellites and terrestrial microwave links for low data rate signals such as teletype, and at sea or in underdeveloped areas. HF radio wave propagation is governed by reasonably well-understood, but not fully predictable, atmospheric phenomena.

Determining the location of an HF transmitter is important since many vessels lack satellite terminals, and maritime distress signals must often be sent by HF, and requires both that a viable propagation path exists between the transmitter and receiver(s), and that the receiving station(s) be listening on the same frequency as the transmitter.

This report reviews some of the fundamentals of HF propagation and investigates the relevance of historical information about which frequencies a given transmitter has used in the past under one set of atmospheric conditions to the question of what frequencies that same transmitter will use under a different, but known, set of atmospheric conditions.

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Introduction

The High Frequency (HF) radio band is commonly taken to be that portion of the electromagnetic spectrum lying between approximately 3 MHz and 30 MHz. (Older texts and some amateur radio operators also call this the 10-meter wave band.) The HF band was the original frequency band of choice for long-haul or beyond line-of-sight (BLOS) communications. Communications satellites and terrestrial microwave links have now assumed much of this role, especially for high data rate signals, e.g. television. However, HF remains a popular and viable alternative for low data rate signals such as teletype, and at sea or in underdeveloped areas. This popularity is due in large part to the low cost of HF components relative to satellites. In addition, for military operations, HF has advantage of being less vulnerable than satellites to certain deliberate countermeasures such as anti-satellite missiles, and provides an important redundancy factor to satellite links.

Determining the location of an HF transmitter, i.e. direction-finding or "fixing," has both important civilian and military applications. For cost reasons, many vessels lack satellite terminals, and therefore maritime distress signals must often be sent by HF. Accurate location of the transmitter of such a distress signal is clearly vital. In the military arena, accurate location of hostile transmitters provides both intelligence and real-time targeting data.

Locating an HF transmitter first requires that it be "heard" at one or more receiving stations, i.e. that a viable propagation path exists between the transmitter and receiver(s). Fortunately, the propagation of HF radio waves is governed by reasonably well-understood atmospheric phenomena. On the other hand, unfortunately, while these phenomena may be well-understood, they are not fully predictable. Therefore, all aspects of the question of whether a given transmitter can be heard (and, if so, how well heard) at a given location, involve a stochastic aspect and some uncertainty.

However, in addition to a viable propagation path existing, "hearing" an HF transmitter also requires the receiver(s) know the frequency that transmitter will use. This report considers, in light of some of the fundamentals of HF propagation, one relevant question concerning the location of HF transmitters:

> *Given historical information about the frequencies which a given transmitter has used in the past under one set of atmospheric conditions, what inferences can be made about the frequencies which that same transmitter will use under a different, but known, set of atmospheric conditions.*

Fundamentals of Propagation of Radio Waves

The earth's atmosphere is a nonmagnetic, overall electrically neutral medium. The propagation of electromagnetic waves in such a medium satisfies Maxwell's equations (Picquenard, [9]):

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$
$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \epsilon_0 \epsilon_r \frac{\partial \mathbf{E}}{\partial t} \tag{1}$$
$$\nabla \cdot \mathbf{E} = \nabla \cdot \mathbf{H} = 0$$

where

$\mathbf{E}$ = the electric field vector
$\mathbf{H}$ = the magnetic field vector
ϵ_0 = the dielectric constant of free space
ϵ_r = the relative dielectric constant of the medium
μ_0 = the magnetic permeability in a vacuum
σ = the conductivity of the medium
$\nabla = \mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y} + \mathbf{k}\frac{\partial}{\partial z}$

Furthermore, the direction of propagation of the energy in the wave is given by

$$\mathbf{E} \times \mathbf{H} .$$

As long as the relative dielectric constant (ϵ_r) is constant (or at least effectively constant relative to the wave length involved), then the electric field satisfies the normal wave equation

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \epsilon_r \frac{\partial^2 \mathbf{E}}{\partial t^2} . \tag{2}$$

($\mathbf{H}$ satisfies the same equation.) In free space or a vacuum (i.e. when $\epsilon_r = 1$), the solutions to this equation are waves which propagate with velocity $c = 1/\sqrt{\epsilon_0 \mu_0}$. When ϵ_r is *not* equal to unity, then one of several possibilities occurs:

- If ϵ_r is a real, positive constant, then the waves propagate without any attenuation at velocity c/n, where n, called the *index of refraction*, is given by $n = \sqrt{\epsilon_r}$. As a consequence of the theory of relativity, $n \geq 1$, and the larger the value of n, the slower the speed of propagation.
- If ϵ_r is purely negative, then waves cannot propagate.
- If ϵ_r is complex, then the waves propagate, but attenuate exponentially with distance. The index of refraction for these waves is given by $n = \sqrt{\Re e(\epsilon_r)^2 + \Im m(\epsilon_r)^2}$.
- If ϵ_r depends on ω (the radian frequency of the wave), then the index of refraction varies with wave length, and non-monochromatic waves *disperse*, i.e. different frequency components get out of phase with each other. (Dispersion causes modulated signals to lose the coherence necessary to accurately transmit information, and thus limits the bandwidth for transmitted signals.) The actual speed of propagation of information (commonly called the group velocity and given by the formula $\frac{d(\omega n)}{d\omega}$) may differ from that given by the index of refraction formula.

- If the index of refraction is not isotropic, i.e. if it varies depending on direction, then, as a consequence of Snell's law, waves passing through the medium will *refract* or bend, from directions of slower travel toward directions of faster travel.

A *dielectric* is a medium in which an applied electric field cannot cause electrons to move, but can induce an effective electric polarization. In a dielectric, ϵ_r is generally real and positive, and, while not necessarily a constant function of position, is also independent of the frequency of an electromagnetic wave. Therefore, HF signals will generally propagate through a dielectric without either dispersion or loss of strength, although their direction may be altered according to Snell's law.

By contrast, when an electromagnetic wave passes through a so-called *plasma*, a gaseous medium which contains free electrons, these electrons try to oscillate at the same frequency as the wave, and therefore propagation may become frequency-dependent. In the simplest case, when the plasma is *weakly ionized*, i.e. when the ratio of free electrons to neutral particles is sufficiently small that the probability of an electron colliding with another particle is small, Picquenard [9] shows that the effective value of the index of refraction becomes

$$n = \sqrt{\epsilon_r} = \sqrt{1 - \frac{{f_c}^2}{f^2}} \tag{3}$$

where f denotes the frequency of the applied wave, and f_c, called the critical frequency, is given by

$$f_c = 2\pi\omega_c = 2\pi\sqrt{\frac{Ne^2}{m\epsilon_0}} \approx 9N^{\frac{1}{2}} \tag{4}$$

(In this representation

$$\begin{aligned} N &= \text{the free electron density} \\ e &= \text{the unit charge of an electron, and} \\ m &= \text{the mass of an electron} \qquad) \end{aligned}$$

According to this formula, and our earlier discussion, waves of frequency lower than f_c will not propagate through this plasma, since that would correspond to a negative value of ϵ_r. Furthermore, waves of frequency higher than f_c which enter the plasma from another region will be refracted (bent) at different angles due to the variation of the refractive index with frequency. Moreover, according to Snell's law, if a wave enters a plasma at an angle (from the vertical) of i_0, from a medium where the refractive index is effectively unity, the angle (i) at which the wave travels in the plasma satisfies

$$n\sin(i) = \sin(i_0) \tag{5}$$

Therefore (since $\sin(i) \leq 1$), any wave for which

$$f < f_c \sec(i_0) \tag{6}$$

cannot enter the plasma, and so must be reflected from the plasma interface back into the original medium.

As the electron density increases in a plasma, this basic refractive behavior continues. However, the process of placing the electrons in the plasma into motion causes a transfer of energy from the forcing wave to the electrons themselves. In a weakly ionized, low-density plasma, this energy subsequently returns to the wave when the field (and hence the electron motion) changes direction. But as the density in the plasma increases, an increasing fraction of this transferred (kinetic) energy in the moving electrons is effectively lost in subsequent collisions involving other particles, and so cannot be returned to the wave. This results in an effective net attenuation of the energy in the wave. This attenuation, also referred to as absorption, is generally more pronounced at lower frequencies.

The Earth's Atmosphere

Most HF radio communication is accomplished via propagation of the signals through the earth's atmosphere. (An HF ground wave may also propagate along the earth's surface, but its effective range is limited to about 300 Km, and therefore its value in long-haul communications is limited.) The earth's atmosphere, as noted earlier, is electrically neutral and nonmagnetic. The atmosphere is however not homogeneous, but composed of several distinctive layers. The location and exact dimensions of these layers (or regions) involves a somewhat arbitrary definition, although most references are in reasonable agreement.

The lowest layer, the troposphere, occupies about the first 10 Km above the earth's surface. This region is normally modeled as a pure dielectric where, due to variations in air density, the index of refraction decreases (i.e. the speed of propagation increases) slightly and slowly with height. Due to the relatively long wavelength of HF signals, the effect of this layer on HF propagation is minimal and HF signals in the troposphere generally propagate in a line-of-sight mode. (The troposphere however exerts significant influence on microwave and similar signals.)

The next layer of interest, the ionosphere, occupies the region from 60-450 Km, and is composed of a mix of particles - some truly neutral (e.g. molecules), and some charged (e.g. electrons and positive ions). (However, since the number of positive and negative charges are equal, the ionosphere remains electrically neutral overall.) As a result, the ionosphere has characteristics that are a mix of a dielectric and a plasma, where the relative ionization defines the ratio of charged to neutral particles. The charged particles are produced primarily by ionizing solar radiation. This production, however, must be continual, since ongoing collisions between positively and negatively-charged particles act to reduce the total number of charged particles.

The ionosphere is the primary medium influencing long-haul HF communications. However, the ionosphere is not homogeneous itself, but composed of several relatively clearly defined layers. The principal of these are

- The *D-region*, which extends from 60-90 Km. This region is present only during daylight periods. The primary effect of the *D*-region is to attenuate HF signals, by transferring energy from the signal to free electrons, which then lose this energy through

random collisions. The attenuation produced by the D-region is most pronounced at lower frequencies.

- The *E-region*, which extends from 100-150 Km. Like the D-region, the E-region is also primarily present only during daylight hours. This region often splits into two sublayers, denoted E_1 and E_2, and may also have small ($\sim$ Km), commonly referred to as sporadic, regions of high local ionization that travel at relatively high speeds and significantly absorb HF energy. During daylight hours, the E-region does reflect some HF frequencies back to earth.
- The *F-region*, which extends from 160-450 Km. During daylight, like the E-region, this region usually splits into two layers, F_1 and F_2, however these layer do not disappear at night, but recombine into a single layer. Reflection from the F-region is the primary source of long-haul HF communication. The F-region also contains traveling ionospheric disturbances (TID's), which are moderately slowly-moving (quasi-period of about 20 minutes) wavelike disturbances that can distort transmission. (According to [9], the physics of the F_2-region are perhaps not as well understood as those of the other regions in the ionosphere.)

HF Propagation in the Ionosphere

The major difference between the ionospheric layers and the uniform plasma described in the previous section is that the density of electrons (N) within each ionospheric layer is not constant, but tends to increase initially with height, then decrease as the top of the layer is reached. The net result of this is that the critical frequency (f_c) will likewise initially increase with height in the lower parts of each layer, then decrease. Consequently, a wave which enters the layer at an angle i_0 will undergo progressive bending away from the vertical as it propagates through these lower parts. Furthermore, by Snell's law (5), if its frequency satisfies

$$f < \hat{f}_c \sec(i_0) \tag{7a}$$

where

$$\hat{f}_c \approx 9 N_{\max}^{\frac{1}{2}} \tag{7b}$$

and $N_{\max}$ is the maximum electron density in the layer, then it will be refracted back toward earth sometime before reaching the level of maximum density. Otherwise, it will pass through this layer to the next one (if any) above. (If this wave is refracted back toward earth, the resulting path can be shown to be identical to a reflection from an interface located at some virtual height, and we shall therefore use the terms refraction and reflection interchangeably in this context.) Generally, the critical frequencies for reflection from the ionosphere fall in the HF region. These reflected waves usually return to earth at a great distance (up to 2000-3000 Km) [6] from the transmitter (far beyond line of sight). This behavior is the principal reason for the utility of HF for long distances communications.

Also according to Snell's law, any wave of frequency higher than $\hat{f}_c \sec(i_0)$ which enters a given ionospheric layer at angle i_0 (or at an angle less than i_0, i.e. more vertically) must likewise pass through the layer. Moreover, any such wave which enters the layer at an angle

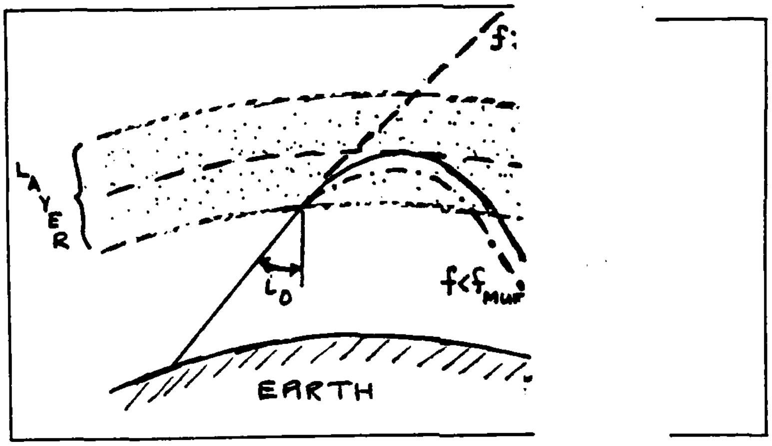

Figure 1 - Ionospheric HF Propagation Paths for a Single Entry Angle

larger than i_0 (i.e. more horizontally) may or may not, depending on Snell's law, be able to be reflected back, but, even if it is, it will return to earth farther from the transmitter than does the wave with frequency $\hat{f}_c \sec(i_0)$. Thus $\hat{f}_c \sec(i_0)$ represents the highest frequency that can be transmitted from a given transmitter to a specific receiver (Figure 1) and is therefore commonly called the maximum usable frequency (MUF), denoted f_{MUF}. (Note that in this figure, for simplicity, we show the ionosphere as only a single layer. For most practical propagation considerations this is adequate, although in reality there are several layers, and some frequencies do not reflect from the lowest, i.e. D, layer.)

Theoretically, according to our discussion so far, any frequency lower than the MUF which enters the ionosphere at i_0 should be capable of reflection back to earth, although, as indicated in Figure 1, it will return at a shorter distance from the transmitter than the MUF. This conclusion, however, neglects the effects of ionospheric absorption of energy which, as noted earlier, affects primarily lower frequencies. Therefore, as a practical matter, there will also be a minimum frequency which is able to propagate into the ionosphere at angle i_0, reflect, and arrive back at earth with sufficient amplitude to still be realistically detectable.

But the reflection criterion (7a) depends not only on the frequency of the wave, but also on the angle at which it enters the ionosphere. Therefore, a wave of lower frequency than the MUF which enters at an angle greater than i_0 (i.e. closer to the horizontal) will also be reflected back to earth, but will arrive further from the transmitter than a wave of the same frequency entering at angle i_0. In theory then, for each frequency lower than the MUF, there will be an entry angle at which a wave of that frequency may also propagate from the given transmitter to the same receiver. (Figure 2.) In practice however, absorption here also helps establish lowest (cutoff) frequency that can practically propagate between two separate points. This cutoff is commonly referred to as the lowest usable frequency (LUF). (In certain cases, a wave of lower frequency than the MUF could actually travel between the prescribed transmitter and receiver by *two* separate paths - the one just described and a second involving a more vertical ($\sec(i_0) \approx 1$) entry into the ionosphere. This second

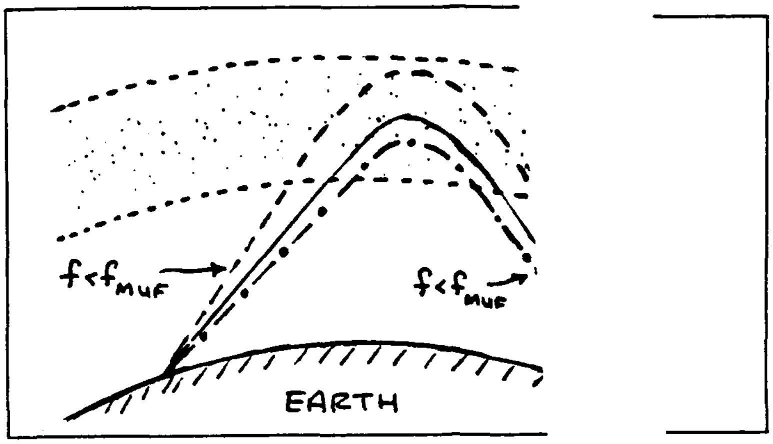

Figure 2 - Ionospheric HF Propagation Paths for Multiple Entry Angles

ray would propagate fairly deeply into the layer (until N became sufficiently large) before reflection. Again as a practical matter, however, absorption normally results in this deeper wave returning to earth with insufficient strength to be detectable.)

In addition, when a reflected wave of a given frequency returns to the earth's surface, some portion of that wave's energy may reflect back upwards, toward the ionosphere, where it can undergo a second reflection ("hop") back to earth. This *multi-hop* transmission further extends the effective range of the transmitter. Moreover, sometimes, due to different angles of entry (i_0) into the ionosphere, parts of the same wave may reach the same destination by more than one path (Figure 3), although the wave traveling the longer path usually arrives with significantly more attenuation. Propagation paths are generally described by the symbol

$${}_{m}L_{n}$$

where

$$m = \text{the number of hops in the path, and}$$
$$L_n = \text{the layer from which reflection occurs}$$

For example, a ${}_3F_2$ path would involve three reflections off the F_2 layer.

Lastly, there are other situations, sometimes bordering on the anomalous, when a wave reflecting down from a higher (E or F) region layer will undergo a subsequent upward reflection from a lower (e.g. D) region, effectively creating a *duct* ([6], p. 17). Waves "trapped" in such ducts may travel 10.000 Km or more before finally returning to earth.

The earth's magnetic field also influences the propagation through the ionized regions, but this effect is not as significant as the basic refraction.

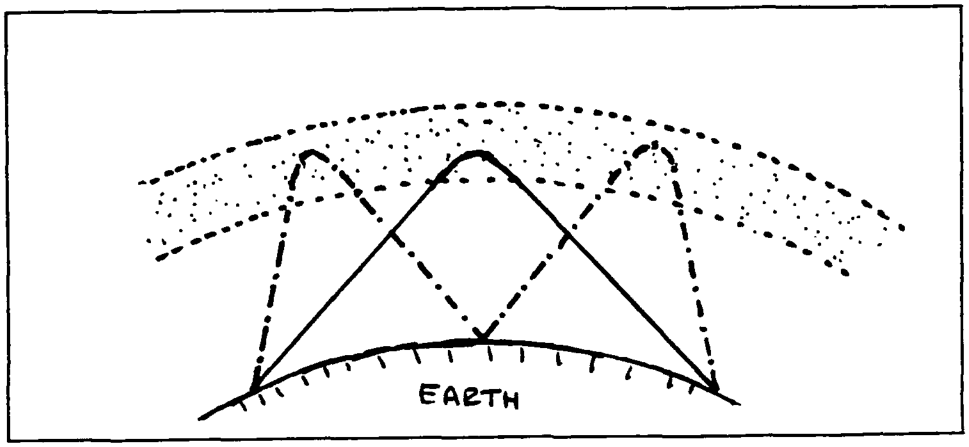

Figure 3 - Multi-Hop Propagation

HF Propagation Prediction

As indicated by the previous discussion, the primary factor influencing HF propagation is the electron density (N) in the various layers of the ionosphere. If this density were completely known at any time, and if the preceding discussion captured *all* of the relevant effects, then predicting the propagation path of any HF signal would be a fairly routine matter. Unfortunately, the electron density changes continually due to various factors, some of which are random, and complete real-time measurement (e.g by radiosonde) would be prohibitively expensive. Moreover, actual HF propagation is also complicated by other horizontally-varying secondary effects, such as the appearance of sporadic E-layers or Traveling Ionospheric Disturbances.

The principal mechanism for producing electrons in the various layers of the ionosphere is incoming solar radiation. The intensity of this radiation depends primarily on the level of solar activity, seasonal factors and, of course, the diurnal cycle. (Regardless of solar activity, ionizing radiation has as about as difficult a time reaching the dark (night) side of the planet as does visible light). Figure 4 displays a typical variation of HF signal strength with time, based on actual measurements, between one particular transmitter and receiver location.)

Fortunately for HF prediction, the mean intensity of incoming solar radiation is highly correlated with sunspot activity. Therefore, an accurate knowledge of the sunspot number should generally be sufficient to permit prediction of the electron densities in the various layers. In fact, according to [9], "most parameters used in the study of the atmosphere are linked with the sunspot number in a simple and rather accurate manner," (p. 104). (He also cautions however (p. 119) that although the "layers vary in altitude and density according to solar cycles ... these variations do not always have the same sense in different layers.") Gurevich and Tsedilina [6], for example, present an empirical, three-dimensional equinoctial model for predicting the electron density at altitudes from 50-500 Km that effectively requires only mean smoothed sunspot (Wolf) number. Their model generally shows excellent fits with mean observations.

Because of the relative accuracy with which atmospheric parameters, and especially the electron density, can be predicted, a number of HF propagation prediction models, nomograms and computer programs have been produced. Their predictions, while not completely accurate, seen sufficiently reliable for most communications circuit engineering purposes. (They are generally weakest at predicting highly transient phenomena, such as TID's.) These models predict primarily the MUF, LUF, and received signal strength for the HF propagation path, if any, between a given transmitter and receiver. As discussed previously, the MUF is the highest frequency that can be reflected back to the receiver and not simply propagate out into space, and the LUF is the lowest frequency that, due to atmospheric absorption, can still be detected at the receiver. (Actually, most models, such as ADVANCED PROPHET [3] calculate not the true MUF, which, because of random and transient variations, is extremely difficult to determine, but the so-called median MUF, a frequency for which the probability that the true MUF is larger is fifty percent.) Most models also predict, and most communications engineers would in practice use a frequency slightly lower than the predicted MUF. This frequency, commonly called the Frequency of Optimum Transmission (FOT), is chosen so that there is a ninety-five percent probability that the true MUF is larger. The FOT represents a practical optimum, since it is normally sufficiently high to avoid excessive absorption, yet sufficiently conservative (relative to the predicted MUF) to ensure a signal path will exist. Figure 5 shows a typical type of HF communication prediction, and is a slight modification of an actual output from ADVANCED PROPHET. (A comparison of figures 4 and 5 indicates the dependence of the MUF and LUF not only on time of day, but on distance also.)

Prediction of the Operating Frequency of a Given Transmitter

HF transmitters operate under fairly well-understood restrictions - they must know the approximate location of the destination receiver and they must choose an operating frequency for which propagation is possible, given the time of day, season and sunspot activity. As discussed above, in most cases the practical frequency of choice would be the FOT for those conditions. However. HF radio frequencies are a limited resource, allocated and used under various international agreements. Consequentially, any given HF transmitter will normally be authorized to operate on only a certain set frequencies, and must choose its actual frequency from this list. Therefore, in most cases, the most likely assumption is that the transmitter will utilize the frequency on its list closest to, but still below, the FOT.

Now consider the effect of a change in the atmosphere on a history of usage of HF frequencies by a particular transmitter, where F_k denotes the k^{th} frequency in this transmitter's list. We shall denote this history by

$$QF_k = \mathbf{P}\{\text{the transmitter used } F_k \text{ for any given transmission}\} \tag{8}$$

A key concern must be the manner in which this history was accumulated. For example, unless subdivided into "bins" by time of day, it would be virtually impossible to separate *a priori* frequency changes made to simply adjust to diurnal changes in the FOT for

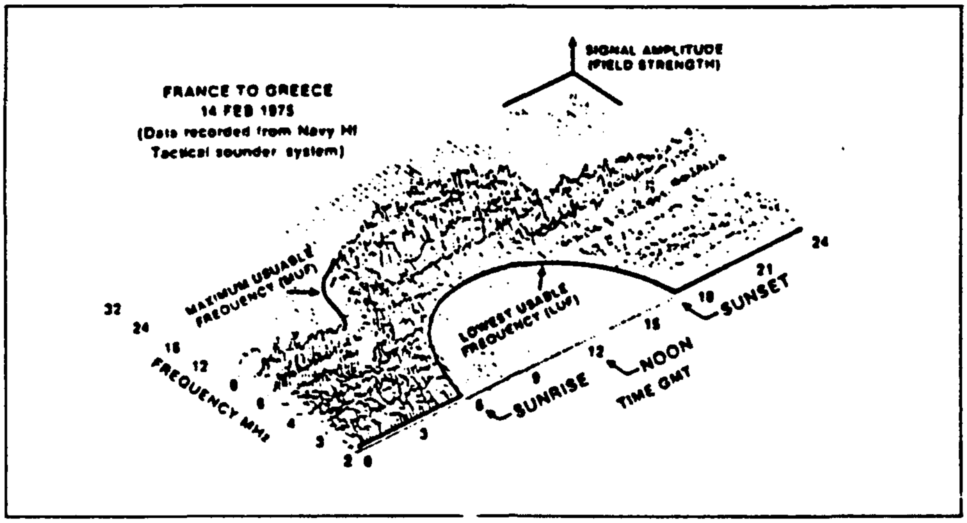

Figure 4 - Measured Signal Strength (from [3])

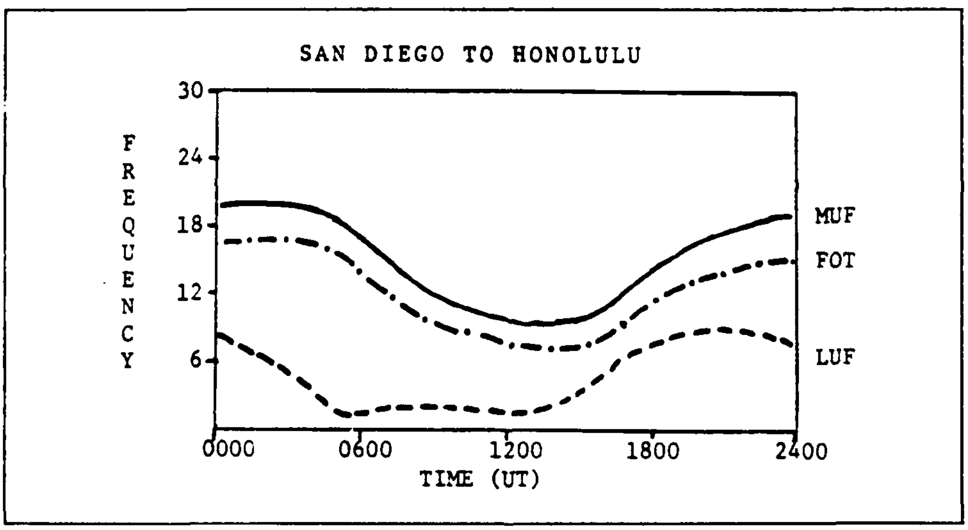

Figure 5 - Predicted Operating Frequencies (adapted from [3])

transmission between the transmitter and a single receiver, as opposed to those made because of transmission to different receivers.

Atmospheric changes, however, affect HF propagation. Therefore, in general, the transmitter of interest will change its frequencies to reflect any significant changes that may occur in the FOT due to atmospheric changes. (This "new" FOT should be predictable, of course, using the same model as predicted the "old" FOT, but updated with the "new" atmospheric parameters and the location of the desired receiver.) Thus atmospheric changes should produce a new history of frequency usage, which we shall denote $\tilde{QF}_k$. If we define

the matrix **A**

$$A_{kj} = \mathbf{P}\{\text{after an atmospheric change } F_k \text{ is the closest authorized frequency below the FOT for the path which previously used } F_j\} \quad (9)$$

then reasonably we would expect

$$\tilde{QF}_k = \sum_j A_{kj}\, QF_j \ . \quad (10)$$

Developing reasonable algorithms for determining the values for A_{jk} *once the FOT after an atmospheric change has been determined* should be relatively simple, provided we assume the transmitter follows the heuristic of choosing the highest allocated operating frequency equal to or below the FOT which meets minimum received signal strength conditions. (We would note that the validity of this formulation also depends critically on several additional assumptions:

- The transmitter does not have any previously unused or reserved frequencies that were not observed during the previous history,
- The transmitter continues to transmit to the same receivers with the same relative proportion of transmissions
- The transmitter is not uncooperative, i.e. that it does not deliberately choose a frequency far from the FOT solely in an attempt to frustrate reception by stations other than the desired receiver.)

How well this approach would perform in practice is, unfortunately, not clear. As we have already noted, for it to work, we must realistically be able to calculate the FOT after any atmospheric changes. However, as we have also noted, determining the new FOT requires knowing both the atmospheric parameters *and* the location of the transmitter's desired receivers, and may be extremely difficult, or even impractical, **unless** these locations are known, e.g. by locating or identifying the receiving station (if and) when it acknowledges receipt of a message from the original transmitter. If the receiving station never transmits, but we were certain that each frequency were being only used for transmission to a single receiver, and we knew the transmitter's location, then we could still possibly infer the location of the receiver. We could do this by using a propagation model and the transmitter's known location to predict where each frequency's path would return to earth. This approach, however, may require some significant judgmental inferences and the existence of important other information when the existence of multi-hop paths implies more than one possible receiver location. Therefore, we cannot, at this juncture, clearly claim that using propagation models to predict $\tilde{QF}_k$ looks highly promising.

There are perhaps other possible methods for attacking the question of predicting $\tilde{QF}_k$. e.g. interpolating based on historical empirical date for varying atmospheric conditions, or perhaps even some kind of Kalman filtering. The fact that the number of independent parameters necessary to capture first-order atmospheric conditions is fairly small makes such ideas at least attractive, although their actual usefulness is highly problematic.

Summary and Conclusions

In this report we have reviewed some of the fundamentals of HF propagation and considered the question of the incorporating historical information about the frequencies which a given transmitter has used in the past under one set of atmospheric conditions to determine what frequencies that same transmitter will use under a different, but known, set of atmospheric conditions.

We have seen that the propagation of HF radio waves is governed by reasonably well-understood principles and atmospheric phenomena. Furthermore, the actual relevant variables are relatively small in number, and their mean values over some reasonable time period can be fairly accurately predicted from the values of a small number of parameters, including the sunspot number, although random or quasi-random effects also exist. Propagation models that provide sufficiently accurate information to determine usable frequencies for communications engineering purposes and that require only minimal atmospheric parameter information do exist. The utility of these models to determine which frequencies a given transmitter will actually use under a given set of atmospheric conditions, however, depends on accurate knowledge of certain other operational information, which may not be available.

Therefore, we do not feel that the use of propagation models to determine the reaction of a given transmitter to changes in atmospheric conditions looks necessarily highly promising at this time.

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